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Fuzzy Modeling in the Management of the Lumber Drying Process

Formalization of uncertainties in the problem

V.V. Pobedinsky
Ural State Forestry University
Ekaterinburg, Russia
pobed@e1.ru

A.G. Gorokhovsky
Ural State Forestry University
Ekaterinburg, Russia

E.F. Hertz
Ural State Forestry University
Ekaterinburg, Russia

E.E. Shishkina
Ural State Forestry University
Ekaterinburg, Russia

A.A. Pobedinsky
Federal State Budgetary Educational
Institution of Higher Education
«Northern Trans-Ural State Agricultural University»
Tyumen, Russia

Abstract— **The problem of lumber drying is considered. The relevance of the research is due to the need to improve the system of automated control of the technological process of drying lumber on the basis of modern information technologies, reducing the energy-intensity of these technologies, which is enshrined in the program documents of forest industry development at the governmental level. It is shown that the most effective solution will be the use of fuzzy modeling. In this case, the characteristics of the uncertainty of the input parameters and the influencing factors will be taken into account. The functional purpose of the automated control system is to provide a given level of moisture content of wood with the required quality of wood (exclusion of damage). It is extremely difficult to obtain such a functional dependence on the heating temperature in the drying chamber and equilibrium air humidity by traditional statistical methods due to the uncertainty of the parameters, therefore, the apparatus of the theory of fuzzy sets should be used for this task. The purpose of this work was to analyze researches in the field of lumber drying and substantiate the meaningful formulation of the problem of moisture content and lumber drying time modeling. The methodological basis of theoretical studies were: the drying theory, wood science, apparatus of mathematical and fuzzy modeling. The result of the research is the substantiation of the meaningful formulation of tasks of fuzzy modeling of the humidity and lumber drying time. The scientific novelty of research follows from the proposed theoretical approach to estimating the parameters of moisture content and drying time of lumber on the basis of fuzzy modeling. The practical applicability of the results lies in the possibility of using the developed problem statement for fuzzy inference of the functional dependence of the control of drying of materials.**

Keywords— wood drying; wood moisture content; equilibrium air humidity; fuzzy modeling

I. INTRODUCTION

The task of increasing energy efficiency has been and remains relevant for the forest industry of the country. The need to stimulate actions for the introduction of energy efficient technologies is directly indicated as one of the global tasks in a number of government documents, for example, in the state policy framework for the period up to 2030[1].

The most energy-intensive processes include the long-term heating of large volumes of raw materials — sawn timber drying. At the same time, in modern woodworking processes, lumber drying is an essential operation, without the correct implementation of which it is impossible to ensure the required quality of any wood products. The difficulty lies in the fact that none of the operations cause such significant changes in the properties of wood as its drying, and this makes the process of controlling the drying chambers extremely unstable. Directly the wood itself is an exceptionally complex material of orthotropic, anisotropic structure, non-uniform structure depending on the breed and the direction of the

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[1] Fundamentals of state policy in the field of use, protection, protection and reproduction of forests in the Russian Federation for the period up to 2030. / Government of the Russian Federation. Order No. 1724-r dated September 26, 2013

section. For these reasons, the working volumes of lumber loaded into the drying chambers may not have the same characteristics, respectively, the present modes usually need to be corrected or adaptively managed throughout the drying process. These modes are determined by the characteristics of the equipment and sawn timber: breed, geometrical parameters, growing area, wood density, place of clipping from the trunk, moisture content, temperature, aerodynamics and thermal equipment of the drying chamber, etc. Thus, in the drying process equipment the most difficult task appears to be technological process managing, due to the diversity of conditions and influencing factors. Currently, work continues on improving the system of automatic control of drying chambers. For example, the purpose of studying the drying process [1] was to obtain the dependence of the moisture content of wood on the temperature of the drying agent. Such a function was necessary to derive the transfer function of the process controller. In this paper, for comparison with theoretical results, experimental data are presented. There are other works that are oriented to modern methods of research and automatic control, but the problem remains unresolved.

Here we have to deal with another problem - the complexity of modeling a multiparameter process. In addition, it should be noted that almost all the parameters of the control process for drying lumber are characterized by uncertainty properties. Modern achievements of mathematics, information technologies, automatic control theory contain an apparatus for creating a perfect system of intelligent automatic control of the drying process, but developments in this direction remain outside the radar of scientists. In studies on this topic, the following features should be taken into account.

1) As is known, the goal of any drying process is to provide a given amount of moisture content in wood with the lowest energy consumption and the required quality (excluding wood damage).The main control parameters of the process are the temperature in the chamber and the equilibrium humidity of the air. The last parameter in the drying chamber can be changed by the organization of air exchange. From the point of view of automatic regulation, it is necessary to obtain a function of the value of wood moisture on the heating temperature and the equilibrium air humidity in the chamber. The moisture content of wood depends on many factors, which in previous studies are described by statistical parameters. But, as already noted, the real parameters are largely characterized by uncertainty properties. In such conditions, it is impossible to obtain a function of wood moisture content depending on a variety of parameters using statistical methods requiring a huge amount of statistical and experimental data. For such conditions, the apparatus of the theory of fuzzy sets (TFS) is used and its application is fuzzy modeling, which has shown its effectiveness in solving the widest class of problems in many branches of science and industry. Extensive experimental results on the topic [1–4] were obtained earlier, the present study is based on them, but known statistics will not be enough to derive a moisture model. A review of some foreign studies [1, 5-17] shows a similar picture, but no results have been obtained for practical application in intelligent control systems. In this case, solving problems of this class is possible using the TFS (theory of fuzzy sets) apparatus, which should determine the relevance, goals and objectives of modern research.

2) From a methodological point of view, it is more expedient to build a system of intelligent automatic control of the drying process on the basis of a fuzzy production neuronet, in the nodes of which there are corresponding fuzzy conclusions from the input parameters.

3) When developing an intelligent system based on a neuronet, each fuzzy inference will be a separate model of the drying process, which may constitute a separate research task.

4) Justification of fuzzy conclusions for such a complex process should be carried out with detailed elaboration of parameters' interaction or a mathematical description of the main processes.

Thus, the objectives of the present studies were determined, the purpose of which was to analyze the research in the field of lumber drying and substantiate the informative statement of the problem of modeling the moisture content and lumber drying time.

The work included the following tasks.

1. Analysis of known studies and identification of sources of uncertainties in the parameters of the wood drying process.
2. Perform meaningful formulation of the task of lumber drying based on fuzzy modeling.

II. REVIEW OF LITERATURE

Analysis of theoretical theses on the topic of wood drying.

The process of wood drying in modeling and developing algorithms for various control systems is generally described as a colloidal capillary-porous body by a system of differential heat and mass transfer equations (HMT) proposed by academician A.V. Lykov [2].

For the simplest case, when total pressure gradients are absent (heat and mass transfer processes during low-temperature convective drying) A.V. Lykov [18] and M.S. Smirnov [19] give the following system of partial differential equations (PDEs):

$$\frac{\partial t}{\partial \tau} = a\nabla^2 t + \frac{\varepsilon\rho}{c}\frac{\partial u}{\partial \tau}, \qquad (1)$$

$$\frac{\partial u}{\partial \tau} = a_m \nabla^2 u + a_m \delta \nabla^2 t, \qquad (2)$$

For an unlimited plate, the initial and boundary conditions of the third kind are:

$$t(x_0, 0) = f(x), \qquad (3)$$

$$u(x, 0) = \phi(x), \qquad (4)$$

$$-\lambda \frac{\partial t(R,\tau)}{\partial x} + \alpha\left[t_c - t(R,\tau)\right] - (1-\varepsilon)\rho\alpha_m\left[u(R,\tau) - u_p\right] = 0, \qquad (5)$$

$$a_m \frac{\partial u(R,\tau)}{\partial x} + a_m \delta \frac{\partial t(R,\tau)}{\partial x} + \alpha_m \left[u(R,\tau) - u_p \right] = 0 \qquad (6)$$

Symmetry condition:

$$\frac{\partial t(0,\tau)}{\partial x} = \frac{\partial u(0,\tau)}{\partial x} = 0, \qquad (7)$$

where *t* and *u* are the temperature and moisture content of the material;

ρ – base material density;

ε – phase transition criterion (is within 0 ≤ ε ≤ 1); when ε = 1, moisture transfer occurs due to vapor diffusion, when ε = 0 in the form of a liquid;

λ – coefficient of thermal conductivity;

a – thermal diffusivity;

a_m – moisture conductivity;

α – external heat transfer coefficient;

α_m – coefficient of external moisture exchange;

δ – thermogradient coefficient;

R –thickness of the half of the plate;

τ – time;

c – heat capacity of the material;

tc –external temperature;

up – equilibrium humidity.

G.S. Shubin [3] noted that various processes of drying and heat treatment of wood can be attributed to two categories:

1. processes in which a phase transition occurs throughout the volume simultaneously or completely absent;
2. processes in which the phase transition boundaries are fixed.

However, despite the differences in the processes, it is possible to describe them with a single system of equations, which is a modification of the equations of A. V. Lykov [2] for the process of drying the object in the form of a plate when deepening for the evaporation zone, as well as the distribution of this system is proposed to the case of variable environmental conditions by volume of material.

In [18], it is noted that the processes of high and low temperature drying can be considered both on the basis of equations with moving boundaries and without them. For low-temperature drying, this is possible in stages with the adoption of moisture conductivity coefficients at averaged temperatures or the heat transfer equation, which requires knowledge of the value of the phase transition criterion ε, but this value is uncertain. In general, the system of equations (8) - (23), as assumed in [19], has no analytical solution in the case of moving phase transition boundaries. Various researchers have solved it by grid methods (or finite-difference methods) using an implicit scheme [3,4], but no satisfactory results have been obtained. The main reasons for this situation are the instability of the source data [4], and from a mathematical point of view of TFS, this can be attributed to the property of data uncertainty.

The conditions of uncertainty most significantly contribute to the following factors:

1) *thermophysical characteristics of wood [4]*

- thermal and moisture diffusivity a и a_m;
- heat transfer and moisture exchange coefficients α и αm;
- phase transition criterion ε;

2) *the parameters of the drying chamber,* which in the calculations are assumed to be constant over the entire volume of the structure, but in reality it is an object with distributed parameters [4];

3) *the lack of reliability of current control of wood moisture* due to the instability of the main parameters significantly reduces the efficiency of control actions of automatic control systems of the parameters of the drying agent.

A. Review of literature on the topic of wood drying

Due to the complexity of the processes of heat and mass transfer in the wood, drying technology has received attention from many scientists. In the publications of foreign authors on the present topic various aspects of this process are taken under consideration. So in the series of works [6], the effect of residual deformations and the rate of compression deformations in different directions on the intensity of wood drying were studied. In this case, the breeds of poplar and Chinese spruce were explored.

In [8], a mathematical description of the process of heat and mass transfer of chamber convective drying of wood and its implementation in the ANSYS Fluent program were proposed. The developed calculation procedure can be used to determine the optimal modes of wood drying.

Studies [9] compared two different methods for assessing the quality of wood drying according to the standards of Australia and New Zealand. Changes in the sample geometry as a result of drying were determined by using an instrument that performs pattern recognition or a mechanical meter. The study showed that, despite the significant difference in the methods, the results of both measurements were identical.

Experimental studies of convective drying are described in [10]. The main results are the dependences of the optimal process parameters on temperature, relative humidity and air flow rate.

The drying process is considered as multi-parameter, therefore, studies were carried out with different goals and different parameters. So in [11], studies of oscillating vacuum-conductive drying are presented, which resulted in the development of a method for calculating the rate of moisture removal from wood during vacuum processing depending on the magnitude of vacuum, temperature, humidity and thickness of lumber.

Some specific features of air circulation were taken into account in [12] when optimizing and modeling drying processes using moisture diffusion models.

In [13], the comparative influence of convective and vacuum drying methods on the mechanical properties of wood was investigated.

Under conditions of drying with cyclic wetting of wood, the components of the cell wall of the wood structure and the parameters of the mechanical strength of the samples were investigated [14].

It should be noted that, in contrast to Russian practice, vacuum drying of wood method and equipment are more widely used abroad. The method has been known since the beginning of the 1900s and accumulated a great deal of experience, therefore, in [15], the results of a review of literature on the technology of vacuum drying of wood are presented. In the proposed classification, the equipment on the basis of the method of heating wood is considered in detail.

In addition to vacuum drying, microwave drying technology is being developed in timber industry countries. This direction is knowledge-intensive and high-tech. The aim of the study [16] was to determine the effect of microwave irradiation on the kinetics of the wood drying process, phytosanitary efficiency and energy consumption for processing, as well as to evaluate the mechanical strength of the dried product. For conditions at a frequency of 2.45 GHz and with radiation power in the range from 300 to 1000 W, a picture of the dependence of speed, drying time and energy consumption on the radiation power, initial temperature of the wood and the geometry of the sample was experimentally obtained.

Of great practical importance for microwave drying is the magnitude of the rate of moisture transfer in the longitudinal direction, due to the driving force and dynamic permeability. The patterns of such a phenomenon are investigated in [17].

Summarizing the review, we can draw the main conclusions in the context of the present research.

1. The results of known studies do not allow to fully solve the problem of automatic control of the wood drying process, primarily because of the uncertainties in the process data.
2. Issues of research of lumber drying processes based on fuzzy modeling have not previously been considered.

III. METHODOLOGY AND RESULTS

The methodological basis of the theoretical studies was constituted by the theory of wood drying, wood science, mathematical and fuzzy modeling..

A. Performing a meaningful formulation of modeling problems, values of humidity and drying time of lumber

In accordance with the well-known methods [20], the formalization of a task begins with a description of data on the main parameters of an object in the form of heuristic rules that simulate the process of drying wood. In this case, changes in the values of moisture and drying time from various combinations of the main influencing parameters are considered. In the informative description of the task, the most specific features of the process are identified. Simultaneously with this procedure, the formation of the rule base of the fuzzy inference system is performed. The process depends on many factors, but we will consider the main parameters that control the convective drying process - these are the current moisture content of lumber and the time it takes to dry. Suppose that the characteristics of the breed, the geometric dimensions of the raw materials, the drying chamber and other influencing parameters are fixed at the same level. Known [4] approximate modes of the drying process conditional timber are shown in table 1.

TABLE I. MODES DRYING OF CONDITIONAL LUMBER

№ stage	**t, ˚C**	**u, %**	**Moisture content of wood, %, W**	**Drying time, h.**
1	69	14.5	60 – 40	39
2	71	12.5	40 – 35	52(+13)
3	73	11.0	35 – 30	67(+15)
4	75	9.5	30 – 25	84(+17)
5	77	7.5	25 – 20	105(+21)
6	79	6.5	20 – 15	132(+27)
7	81	5.5	15 – 10	170(+38)
8	83	4.0	10 – 8	192(+22)

The drying process is highly non-linear, therefore it is divided into 8 steps for analysis. The moisture content of wood is inversely proportional to temperature and inversely proportional to equilibrium air humidity. Drying time in the range of humidity from 60 to 40% is the longest and for conditional lumber is 39 hours. Further, it decreases, but in comparison with the following steps this is explained by the magnitude of the change in humidity only by 5%. Regarding humidity, the longest drying time is at the eighth stage, where the drying time needed to ensure a 2% moisture reduction is 22 hours.

B. Scientific novelty

The scientific novelty of the results is determined by the first proposed theoretical approach to estimating the parameters of moisture and drying time of lumber based on fuzzy modeling. Another element of the scientific novelty is the informative formulation of the task of fuzzy process modeling.

C. Practical applicability

The practical applicability of the research results lies in the possibility of using the obtained formulation of the task of fuzzy inference of functional dependence of lumber drying controlling, and is ultimately necessary for the development of a fuzzy drying chamber controller.

IV. CONCLUSION

Studies have led to the following conclusions:

1. At present, the improvement of research methods for the parameters of wood drying is impossible without the use of intelligent software systems and computer tools. The proposed formulation of the fuzzy modeling problem makes it possible to effectively use information technology in research, modeling and improvement of drying chambers.
2. Development/elaboration of a model for estimating the moisture content of sawn timber using statistical methods is extremely time-consuming and will not be a sufficiently correct approach. For the conditions of this class of problems, the apparatus of fuzzy sets is most suitable.
3. The proposed formulation of the problem allows to implement a fuzzy inference procedure and obtain a resulting model for drying lumber.

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